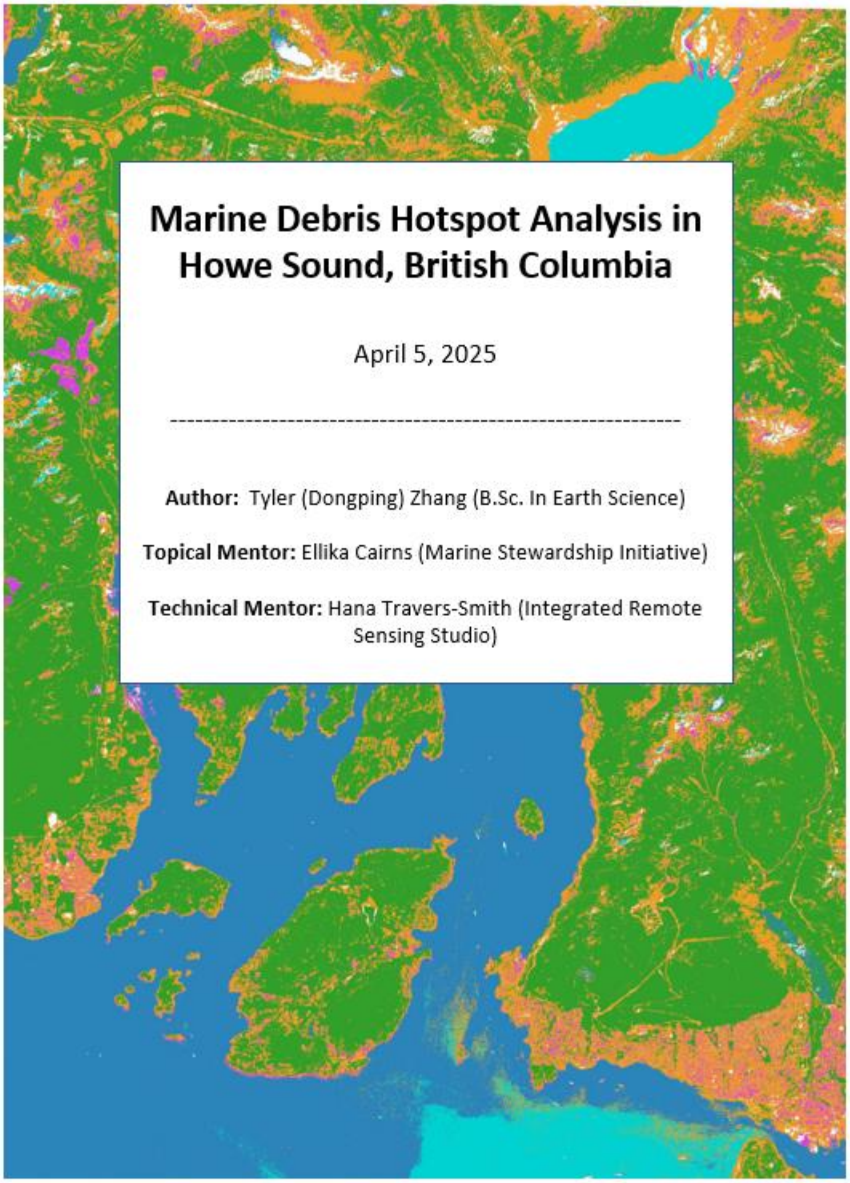

Marine Debris Hotspot Analysis in Howe Sound, British Columbia

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Author: Tyler (Dongping) Zhang (B.Sc. In Earth Science)

Topical Mentor: Ellika Cairns (Marine Stewardship Initiative)

Technical Mentor: Hana Travers-Smith (Integrated Remote Sensing Studio)

Abstract

Marine debris poses significant threats to coastal ecosystems and infrastructure, especially in semi-enclosed regions where monitoring is limited by inaccessibility and uneven population distribution. In Howe Sound, British Columbia, this study integrates remote sensing and environmental modeling to predict debris accumulation hotspots. Sentinel-2 satellite imagery was selected due to its high spatial resolution, broad spectral range, and frequent revisit time, which make it well-suited for capturing detailed coastal features. A neural network algorithm was used to classify six landcover types with an overall accuracy of 0.98. The classification results showed that many known debris hotspots are located near urban shorelines and within semi-enclosed bays. To simulate debris transport, river discharge and seasonal wind direction were modeled as surface movement drivers. The study area was divided into three sections to account for spatial variation in debris driving forces contribution. Hourly wind data from four weather stations were used to construct wind rose diagrams that captured seasonal changes in wind direction. The simulation identified 49 predicted debris hotspot locations. Of these, 20 overlapped with known hotspots, while 10 of the 29 newly identified hotspots are in less populated and previously underreported areas, particularly along the western shoreline. These findings demonstrate that remote sensing, when combined with physically based modeling, can overcome limitations of traditional monitoring methods and improve the identification of marine debris accumulation. This approach provides a scalable and transferable framework for supporting more targeted and proactive coastal management strategies.

Keywords: Howe Sound, Debris, Hotspot, Simulation, Classification

1.Introduction.

An estimated 1.15 to 2.41 million tons of human-produced plastic waste enter the ocean each year, posing significant risks to marine ecosystems by entangling wildlife, introducing toxic pollutants, disrupting habitats and biodiversity, and endangering community safety through damage to coastal roads and sewer infrastructure (Kye et al., 2023; L. C. M. Lebreton et al., 2017; Lincoln et al., 2022). Howe Sound is a coastal fjord in southwestern British Columbia that hosts diverse ecosystems and serves as a vital habitat for various marine species, including juvenile salmon and numerous water birds (Butler et al., 2020; Lingard, 2023). It also holds deep cultural significance for the Coast Salish people (Ford, 2024). Analyzing and predicting debris hotspots in Howe Sound has the potential to greatly enhance local cleanup efforts, making them more efficient, targeted, and cost-effective. By identifying where debris is most likely to accumulate, resources can be allocated strategically, reducing the environmental footprint of marine litter before it causes further harm. This has direct implications for preserving wildlife habitats, as entanglement and ingestion of plastic waste continue to threaten marine species in the region. Currently, no studies have predicted where debris tends to accumulate in Howe Sound, and hotspot identification relies on resident reports, which are often biased due to uneven population distribution. This research ultimately supports a more informed, place-based approach to environmental management in Howe Sound.

To better understand and predict where marine debris accumulates in Howe Sound, this research takes a two-part approach. First, it analyzes patterns in landcover at known debris hotspot locations using supervised classification of satellite imagery. Remote sensing is well-suited for this work because it allows for consistent, large-scale monitoring of coastal environments that may be difficult to access on foot and are often underreported due to uneven population distribution (Sun et al., 2024). Compared to traditional survey methods, satellite imagery provides a more comprehensive and unbiased view of the landscape. The second part of this research involves developing a debris movement simulation model that incorporates environmental driving forces, specifically wind patterns and river discharge to predict where debris is likely to travel and accumulate in the future. Together, these methods aim to identify at-risk zones in Howe Sound and support more proactive coastal management strategies."

Marine debris does not accumulate randomly, it moves according to environmental forces and interacts with coastal geography. Understanding these forces is key to identifying where debris is likely to cumulate. In coastal systems like Howe Sound, surface layer movement is primarily driven by wind, river discharge, and tidal currents (Jambeck et al., 2015). The relative influence of these forces varies throughout the fjord: in the north, near the head of the fjord, river discharge from the Squamish River is the primary source of spatial inhomogeneity in the surface water, while in the south, near the Strait of Georgia, wind becomes the primary driver of surface water transport (Buckley, 1977). The interaction between environmental driving forces and coastal topography, including bays, headlands, and islands, plays a critical role in shaping the movement of floating debris. Together, these factors help predict where debris is most likely to travel and accumulate, particularly in areas where geographic features naturally trap floating material.

Remote sensing offers a powerful way to observe the spatial patterns associated with debris accumulation (Veettil et al., 2022). Using satellite imagery, we can monitor coastal landforms, shoreline vegetation, and human-altered landscapes, factors that influence where debris tends to settle. When paired with a simulation model that incorporates environmental drivers like wind and river discharge, satellite-based landcover observations provide valuable context for understanding why certain areas become debris hotspots. This integrated approach allows for both detection and prediction, offering a more complete picture of marine debris dynamics in Howe Sound.

2. Study Site and Data Summary

Howe Sound is a glacial fjord located in southwestern British Columbia, extending from the mouth of the Squamish River in the north to the Strait of Georgia in the south. It is characterized by steep mountainous terrain, sheltered bays, and numerous islands that create a highly dynamic coastal environment. These physical features influence water circulation patterns and play a significant role in the transport and accumulation of marine debris (Buckley, 1977).

To explore the spatial patterns of debris accumulation and the environmental factors influencing them, this study draws upon three main sources of data: hourly wind direction data, satellite imagery, and spatial records of known debris hotspots.

Wind Data

Historical hourly wind direction data were collected from four weather stations located throughout the Howe Sound region. These data were accessed through the Government of Canada's "Weather, Climate and Hazard" archive. The selected stations include Squamish Airport, Pam Rock, Port Mellon, and Point Atkinson as shown in Fig 1. These four stations were chosen because they are the only stations within Howe Sound that provide hourly wind direction data and their distribution across different sections of the fjord enables the identification of regional variations in seasonal wind patterns. The data were downloaded as CSV files and processed to calculate average wind direction for both summer and winter. These seasonal wind trends are used to simulate debris movement across the surface layer of the water.

Satellite Imagery

To classify coastal landcover and examine its relationship to debris accumulation, Sentinel-2 imagery was selected for its high spatial resolution, broad spectral range, and open-access availability. Operated by the European Space Agency under the Copernicus Program, Sentinel-2 consists of two satellites launched in 2015 and 2017, carrying a Multispectral Instrument with 13 spectral bands at 10–60-meter resolution (Drusch et al., 2012). Compared to Landsat's 30-meter resolution and Planet Scope's high cost, Sentinel-2 offers an ideal balance of detail, frequency, and accessibility. Imagery from late summer to early fall was downloaded from the Copernicus Open Access Hub to ensure minimal cloud cover and stable seasonal conditions. Bands 2 (blue), 3 (green), and 4 (red) were used to generate a true-color composite at 20-meter resolution. The data were processed in QGIS using supervised classification to identify landcover classes such as forest, urban areas, open water, and shoreline features.

Debris Hotspot Data

Shapefiles of known debris hotspot locations were obtained from the Marine Stewardship Initiative. These records are based on spatially referenced reports of marine debris collected from

October 2022 to October 2024 by community monitoring efforts. The hotspot locations are used to provide reference points for building the debris movement simulation model and to validate the simulation results. Figure 1 shows the distribution of the four selected weather stations along with the seasonal wind direction diagram, Figure 2 illustrates the distribution of known debris hotspots in Howe Sound.

Together, these datasets offer a comprehensive view of Howe Sound's physical and environmental characteristics and provide the foundation for modeling debris transport pathways and identifying new debris hotspots.

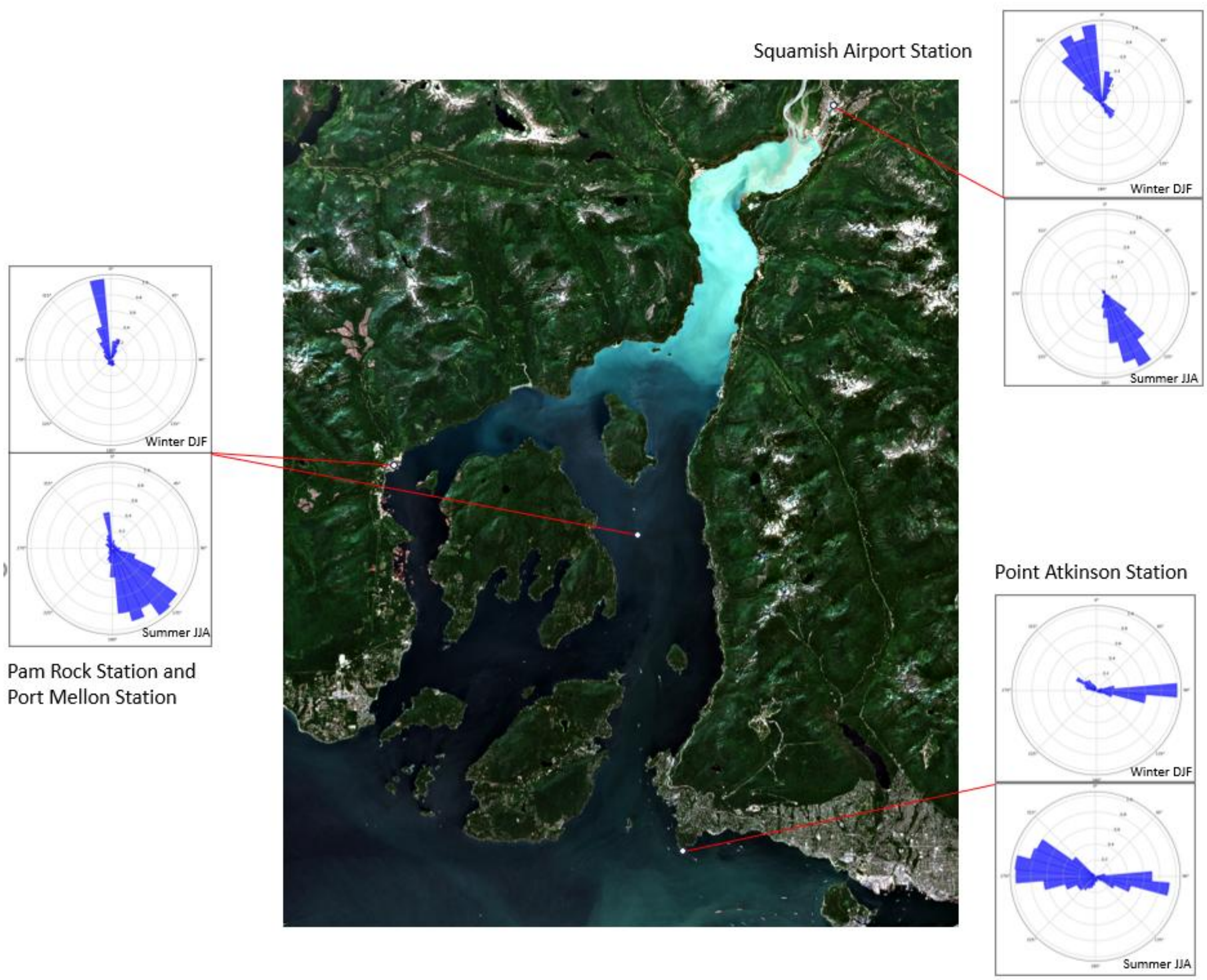

Figure 1. Wind rose diagram showing daytime wind direction at the four chosen stations in Howe Sound

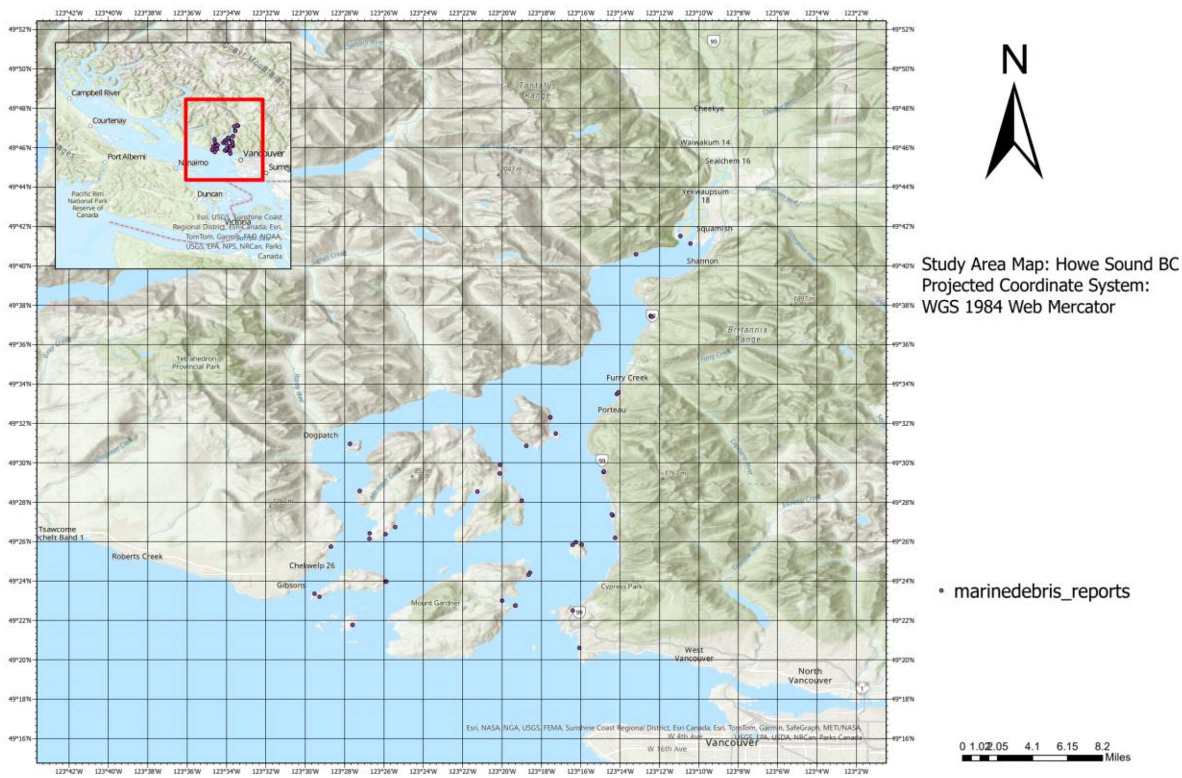

Figure 2. Existing debris hotspot locations in Howe Sound from Marine Stewardship Initiative Database collected from October 2022 to October 2024 by community monitoring efforts

3. Method.

3.1 Supervised Classification.

In order to understand the relationship between debris hotspot locations and land cover types in Howe Sound, this study utilizes multi-band Sentinel-2 satellite imagery from both summer and winter and apply supervised classification to classify landcover into landcover classes. Bands 2 (blue), 3 (green), and 4 (red) from Sentinel-2, each with a 20m resolution will be used to generate a true-color composite raster image of Howe Sound. This image will be imported into QGIS, where a polygon layer of training data will be manually created by drawing polygons over the true-color composite. The training dataset will consist of labeled polygons representing six distinct land cover types: vegetation, ocean water, river discharge, urban areas, snow, and exposed rock. These categories were selected as they are the most commonly observed land cover types in Howe Sound. The training samples will be used to train the classifier. Based on spectral characteristics, each pixel in the raw, unclassified image will be assigned to one of the six land cover categories. Multiple classification algorithms were tested in this study, including Maximum Likelihood Classification (MLC), Random Forest, and a neural network. MLC is a widely used parametric method in remote sensing (Otukei & Blaschke, 2010), while Random

Forest has gained popularity for its high accuracy and ability to handle complex data structures in landcover mapping (Belgiu & Drăguţ, 2016). Neural networks, particularly convolutional models, have shown strong performance in image classification tasks by learning spatial and spectral patterns (Krizhevsky et al., 2012). The final classified image will be selected based on the highest accuracy. Once classification is complete, a shapefile of existing debris hotspot locations, obtained from the Marine Stewardship Initiative database, will be overlaid on the classified map to analyze the commonalities in landcover classes at debris hotspots.

3.2 Debris transport pathway simulation model

To predict debris hotspot locations in Howe Sound, this study develops a debris movement pathway simulation model that incorporates key environmental drivers of surface transport. Similar models have been used in coastal and estuarine environments to simulate the movement of floating marine debris based on wind, currents, and freshwater input (L. C.-M. Lebreton et al., 2012; Maximenko et al., 2012). These models often rely on vector field representations of surface forces to estimate transport pathways and accumulation zones. In this study, wind and river discharge are modeled as vector fields over sectional basemaps of Howe Sound, generating a smooth, continuous animation of debris movement over time.

A cartographic boundary file for Howe Sound obtained from Statistics Canada will be used as the base map. As demonstrated by Buckley (1977), the influence of surface layer water driving forces varies across different sections of Howe Sound. Based on these variations in surface water dynamics, the study area is divided into three sections: Northern, Central, and Southern Howe Sound shown in Figure 3. Northern Howe Sound extends from the town of Squamish at the fjord’s northern end to Britannia Beach. Central Howe Sound spans from Britannia Beach to Anvil Island, while Southern Howe Sound stretches from South Anvil Island to the Strait of Georgia.

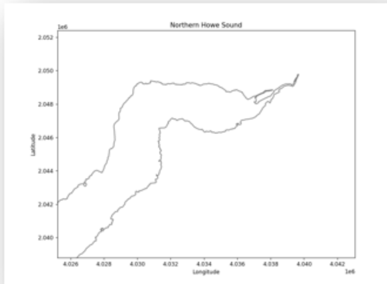

Fig3-1 Northern Howe Sound Basemap

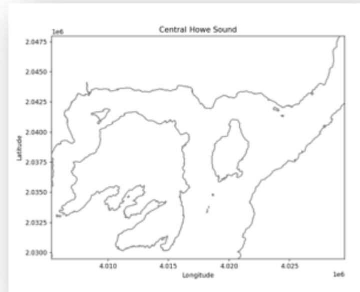

Fig3-2 Central Howe Sound Basemap

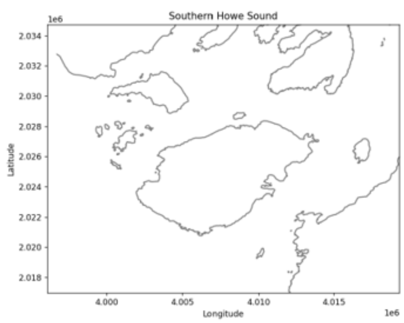

Fig3-3 Southern Howe Sound Basemap

Figure 3. Howe Sound basemap split into 3 sections base on variation in surface water movement driving force.

Water movement in each section will be represented as a vector field on the basemap, reflecting differences in the dominant driving forces. Each driving force will be expressed as a separate vector field. In the northern section, where Squamish River discharge is the primary driver of spatial inhomogeneity and dominates surface water movement (Buckley, 1977), wind and tides primarily introduce short-term small-scale fluctuations in the surface layer. Consequently, river runoff is weighted more heavily than wind in the water movement model.

To simulate river discharge, the model incorporates a fan-shaped spreading function, which represents how river plumes expand as they enter a larger body of water due to the loss of channel confinement (Osadchiev & Sedakov, 2019). As noted by Bakri et al., (2017), Howe Sound experiences a seasonal shift in wind direction with prevailing patterns differing between summer and winter. To account for wind effects, hourly wind data from 2017 to 2020 for both summer months (June, July, and August) and winter months (December, January, and February) will be used to generate wind rose diagrams for each section of Howe Sound, illustrating the most frequent wind directions. To better illustrate the seasonal shift in wind direction, an additional wind rose plot was generated using only daytime wind data because solar heating plays a major role in driving local wind patterns, reducing the influence of nighttime cooling effects and localized drainage winds. The selected weather stations include Squamish Airport for Northern Howe Sound, Pam Rock and Port Mellon for Central Howe Sound, and Point Atkinson for Southern Howe Sound. These stations were chosen based on their proximity to their respective sections and because they are the only stations within Howe Sound that record hourly wind direction data.

As demonstrated by Blanchfield (2007) and Buckley (1977), tidal currents in Howe Sound follow a semidiurnal pattern (Blanchfield, 2007; Buckley,1977). These semidiurnal tidal currents were excluded from the simulation due to the difficulty of incorporating semidurnal processes into a seasonal simulation model.

The final debris movement visualization is generated as a time-dependent animation, illustrating how debris is transported under the influence of wind and river discharge. Water movement pathways are overlaid on the base map of each section in Howe, these pathways are represented as continuous moving lines with a fading effect at the end of each cycle, animated using the open-source Python library Matplotlib (Hunter, 2007). Debris hotspots are expected to form in the vicinity of points where movement pathways intersect with the coastal boundary. By examining the surrounding landform features, such as enclosed bays, headlands, or other coastal structures, we can accurately pinpoint potential debris hotspots.

4. Result

4.1 Landcover classification

Satellite imagery from Sentinel-2 was classified into six distinct land cover classes using neural network techniques, as shown in Figures 4 and 5. Existing debris hotspot locations were overlaid on the classified summer satellite map. The neural network classification achieved an accuracy of 0.98 for the summer image and 0.97 for the winter image, slightly outperforming the Random Forest classifier, which achieved 0.97 for both summer and winter. The Maximum Likelihood Classification (MLC) method performed comparably in summer with an accuracy of 0.97 but showed a notable decline in winter, achieving only 0.87.

Actual	Exposed Land	Ocean	River	Snow	Urban	Vegetation	User's Accuracy
Predicted							
Exposed Land	739.000	0.000	0.000	4.00	277.000	0.000	72.45
Ocean	0.000	19222.000	0.000	0.00	0.000	2.000	99.99
River	0.000	0.000	11616.000	0.00	5.000	0.000	99.96
Snow	2.000	0.000	0.000	497.00	6.000	0.000	98.42
Urban	239.000	0.000	0.000	10.00	778.000	1.000	75.68
Vegetation	11.000	41.000	33.000	0.00	266.000	12087.000	97.18
Producer's Accuracy	74.571	99.787	99.717	97.26	58.408	99.975	NaN

Table 1. Confusion matrix for the neural network classification of the summer image.

Actual	Ocean	River	Snow	Soil	Urban	Vegetation	User's Accuracy
Predicted							
Ocean	29846.000	108.000	0.000	0.000	0.000	46.000	99.49
River	6.000	10.000	0.000	0.000	1.000	5.000	45.45
Snow	0.000	0.000	18108.000	20.000	71.000	4.000	99.48
Soil	0.000	0.000	244.000	1804.000	185.000	76.000	78.13
Urban	0.000	0.000	376.000	52.000	2408.000	203.000	79.24
Vegetation	554.000	49.000	71.000	1.000	183.000	20329.000	95.95
Producer's Accuracy	98.158	5.988	96.324	96.111	84.551	98.384	NaN

Table 2. Confusion matrix for the neural network classification of the winter image.4

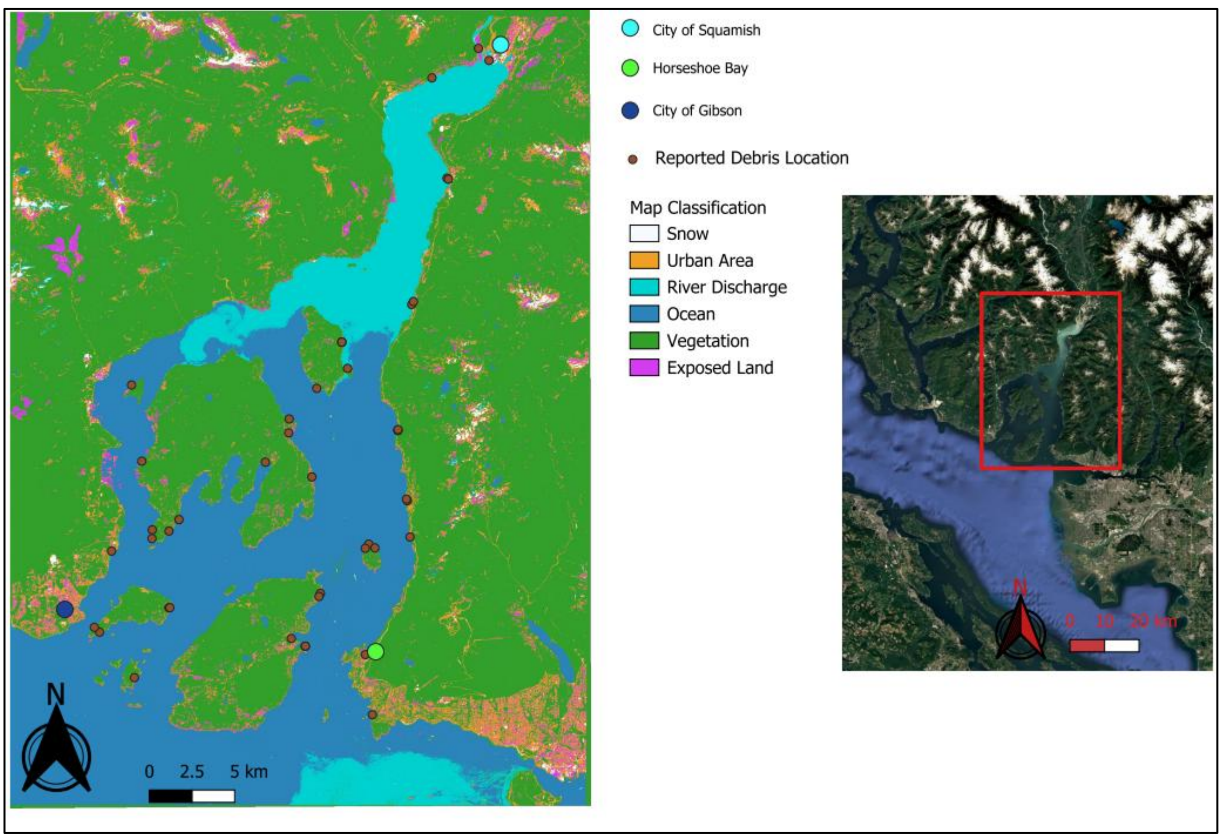

Figure 4. Supervised classified map of a summer day satellite image of Howe Sound using neural network techniques

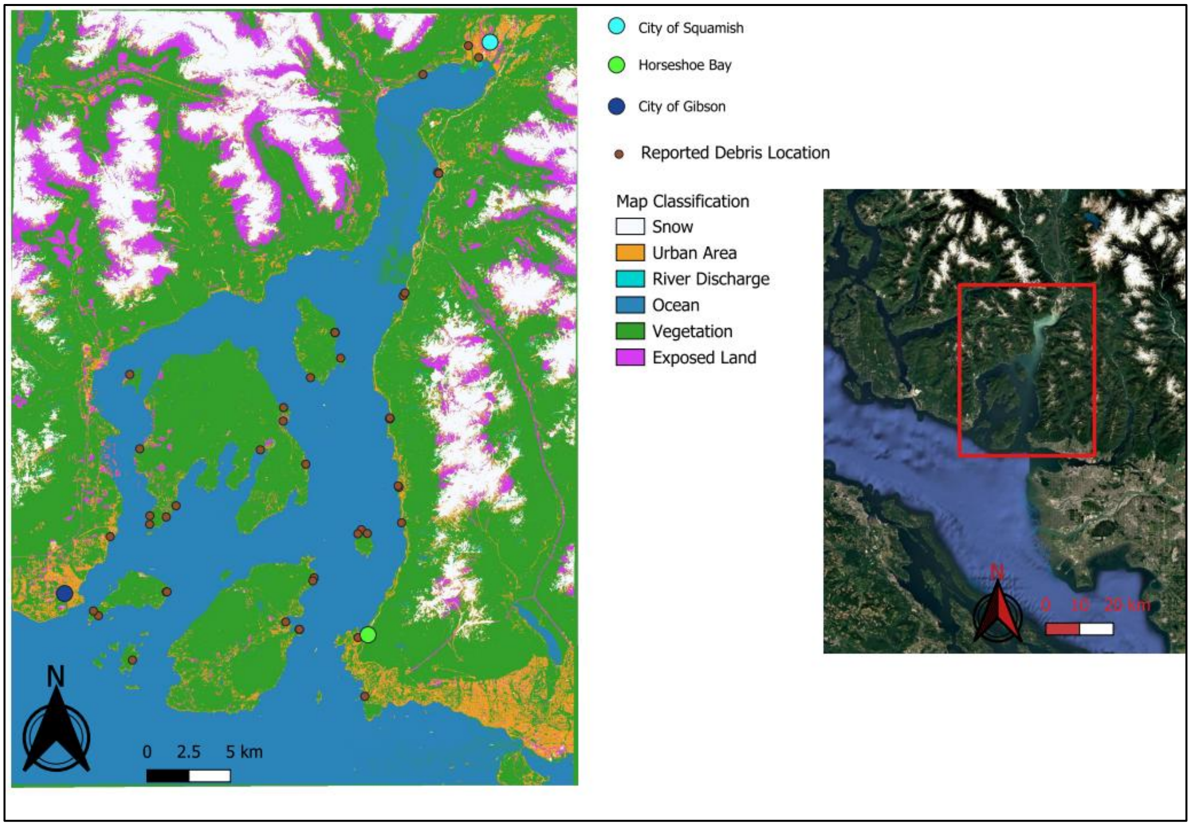

Figure 5. Supervised classified map of a winter day satellite image of Howe Sound using neural network techniques

The classified maps reveal a substantially smaller snow-covered area in the summer image (Figure 4), while the winter map shows a notable reduction in river discharge. These findings indicate that river discharge is a major driving force for debris accumulation in the northern and central regions of Howe Sound, but only during the summer season.

Another key observation from the classification maps is there is a noticeable absence of debris hotspots along the western shoreline of Howe Sound. This distribution is largely due to the fact that debris hotspot identification relies heavily on reports from local residents.

4.1 Debris transport pathway simulation model

Wind rose diagrams for summer (June–August) and winter (December–February) at Squamish Airport, Point Atkinson, Pam Rock, and Port Mellon stations are shown in Figure 6. Figure 7 presents wind rose plots using only daytime wind data to better illustrate the seasonal wind shift. The results are in good agreement with the wind rose plots produced by Talaat et al. (2016). In Northern Howe Sound, outflow winds dominate in winter, while inflow winds from the south prevail in summer. Central Howe Sound exhibits a similar seasonal pattern. In Southern Howe Sound, winds primarily come from the east during winter and shift to westerly directions in summer.

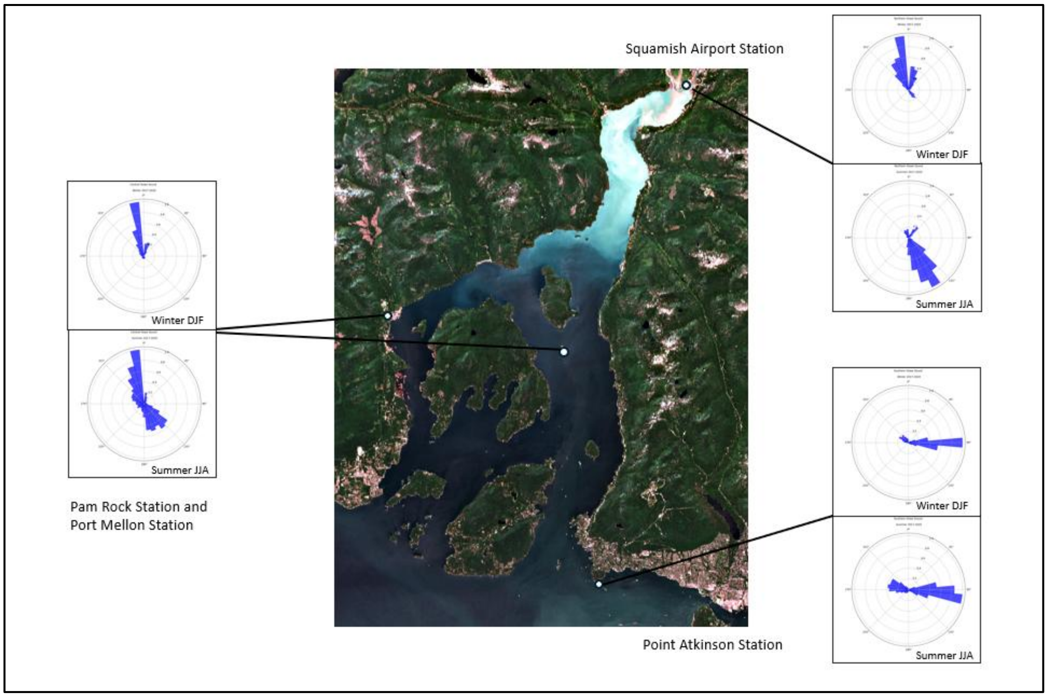

Fig 6. Wind rose plots for summer (June–August) and winter (December–February) at Squamish Airport, Point Atkinson, Pam Rock, and Port Mellon stations.

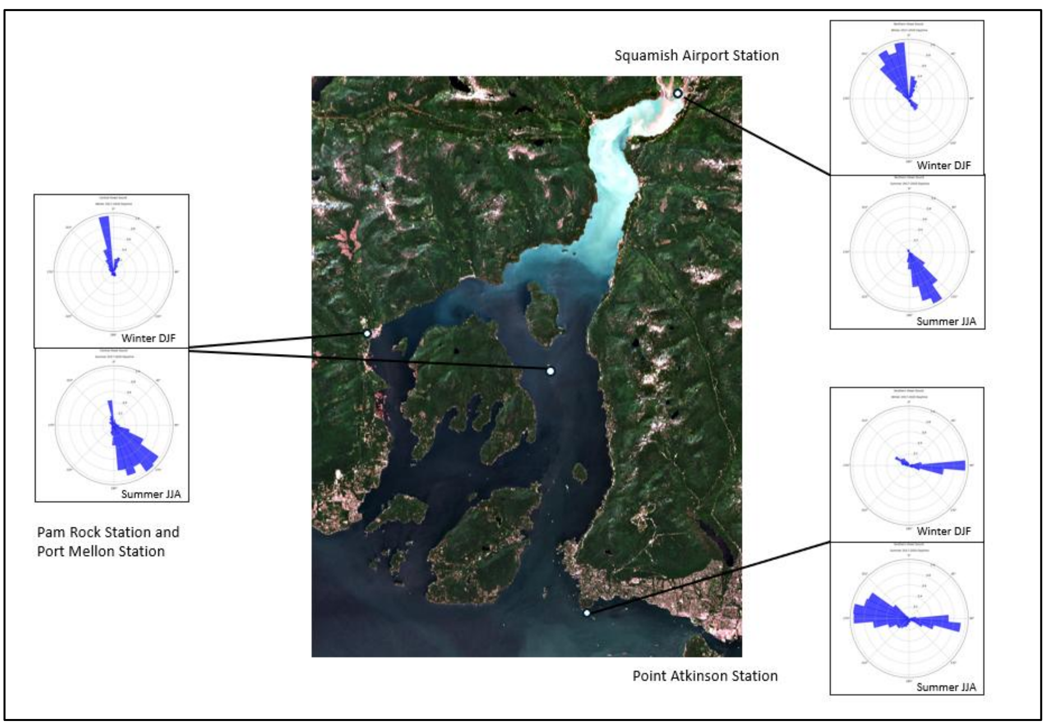

Fig 7. Daytime Wind rose plots for summer (June–August) and winter (December–February) at Squamish Airport, Point Atkinson, Pam Rock, and Port Mellon stations.

The debris transport simulation model identified 49 debris hotspot locations across Howe Sound. 20 of the predicted hotspots overlapped with existing hotspot reports from the Marine Stewardship Initiative database shown in Figure 8, indicating a high degree of agreement between modeled outputs and community-reported observations. 10 of the remaining 29 predicted hotspots were located in areas that had not been previously reported along the western shoreline of Howe Sound between the Squamish River estuary and Port Mellon. These locations are generally less populated and may have been underrepresented in community reports due to reduced local monitoring.

Fig 8. Predicted ad existing debris hot spot in Howe Sound

5. Discussion

5.1 Summary of key findings

Marine debris is an escalating environmental threat, particularly in coastal fjords such as Howe Sound, British Columbia. With estimates suggesting over 1 million tons of plastic waste entering the ocean annually (L. C.-M. Lebreton et al., 2012), accurate identification of debris accumulation zones is crucial. Current monitoring methods in Howe Sound rely heavily on resident reports, which are often incomplete due to sparse population in remote regions. This study developed a debris movement simulation model for Howe Sound, British Columbia, incorporating river discharge and wind as primary driving forces. The results identified 49 debris hotspots, 20 of which overlapped with existing reported hotspots, demonstrating the model's ability to predict debris accumulation areas. The findings confirm that river discharge is the dominant force in northern Howe Sound near the Squamish River mouth, while wind-driven transport is the primary mechanism in the southern fjord. The seasonal variation in wind patterns also influences debris dispersion. For instance, in southern Howe Sound, strong east winds in the winter months and strong west winds in the summer months significantly influence debris movement pathways, creating different debris hotspot locations.

5.2 Comparison between newly predicted hotspot and existing hotspot

Prior studies have shown local topography and hydrodynamic conditions play a significant role in debris accumulation(Hernandez et al., 2025; Suara et al., 2020). Analysis of landcover characteristics at hotspot locations revealed similarities between model-predicted and existing debris hotspots. Many of these sites share common geographic features, such as proximity to semi-enclosed bays and wind-sheltered areas.

While 20 of the model-predicted hotspots overlapped with existing debris hotspot reports, the remaining 29 predicted hotspots did not match current observations. A potential reason for this discrepancy is the reliance on resident reports for the existing hotspot identification. Since some areas in Howe Sound are less populated, such as the western shoreline, fewer reports may have been made for locations that still accumulate debris. This model significantly addresses that issue, identifying 10 debris hotspots along the western shoreline of Howe Sound from the Squamish River estuary to Port Mellon. These findings suggest that previously unreported debris accumulation areas exist, highlighting the need for systematic monitoring beyond community-reported observations.

5.3 Area for Improvement

Prior studies have identified wind as the primary driver of surface water transport in Howe Sound (Buckley, 1977). However, the simulation model in this study relies on seasonal average wind directions, which may not capture short-term variability, such as storm-driven debris movement. Additionally, there are currently only four weather stations in Howe Sound that record hourly wind direction data, one in the northern region, one in the south, and two in the central section. Incorporating higher-resolution, real-time wind data from additional stations and accounting for extreme weather events could improve the accuracy and responsiveness of the model.

Additionally, a similar study by Tsiaras et al. (2021), which modeled the pathways and accumulation patterns of marine debris in the Mediterranean, highlighted the importance of vertical mixing in accounting for the dispersion of debris throughout the water column due to turbulence. Incorporating vertical mixing into the current model could enhance its accuracy by capturing how debris moves not only at the surface but also through different depths of the water column.

Furthermore, while the current model accounts for debris origin points by placing more debris starting points near the Squamish River mouth and densely populated areas such as the city of Squamish and along Highway 99 on the eastern shoreline, it does not use a formal weighted probability map to represent source intensity. Future iterations of this model could be improved by incorporating mapped debris origin points or assigning weighted probabilities to areas that are more likely to generate debris. This would enhance the simulation's realism and improve its accuracy in predicting where debris is likely to travel and accumulate.

Moreover, although tidal currents are recognized as influential in Howe Sound (Blanchfield & Eng, n.d.), they were excluded from the current model because incorporating a semidiurnal process into a seasonally scaled simulation would introduce a level of temporal complexity that exceeds the scope of this study. Future iterations of the model could consider integrating tidal dynamics to better capture their potential influence on debris transport pathways. Finally, as emphasized by (Otukei & Blaschke, 2010), ground-truth validation is important for model and classification improvement. Conducting field visits to predicted hotspots particularly in underreported areas would enable validation and model refinement.

Understanding how debris accumulates in Howe Sound can inform targeted cleanup efforts and coastal management strategies. Adaptive modeling approaches, incorporating real-time environmental data, will be crucial for maintaining accurate debris predictions. The methodologies applied in this study could be extended to other coastal or semi-enclosed water bodies to improve marine debris management worldwide.

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